Challenges in Solid-State Batteries toward Applications in Extreme Space Environment

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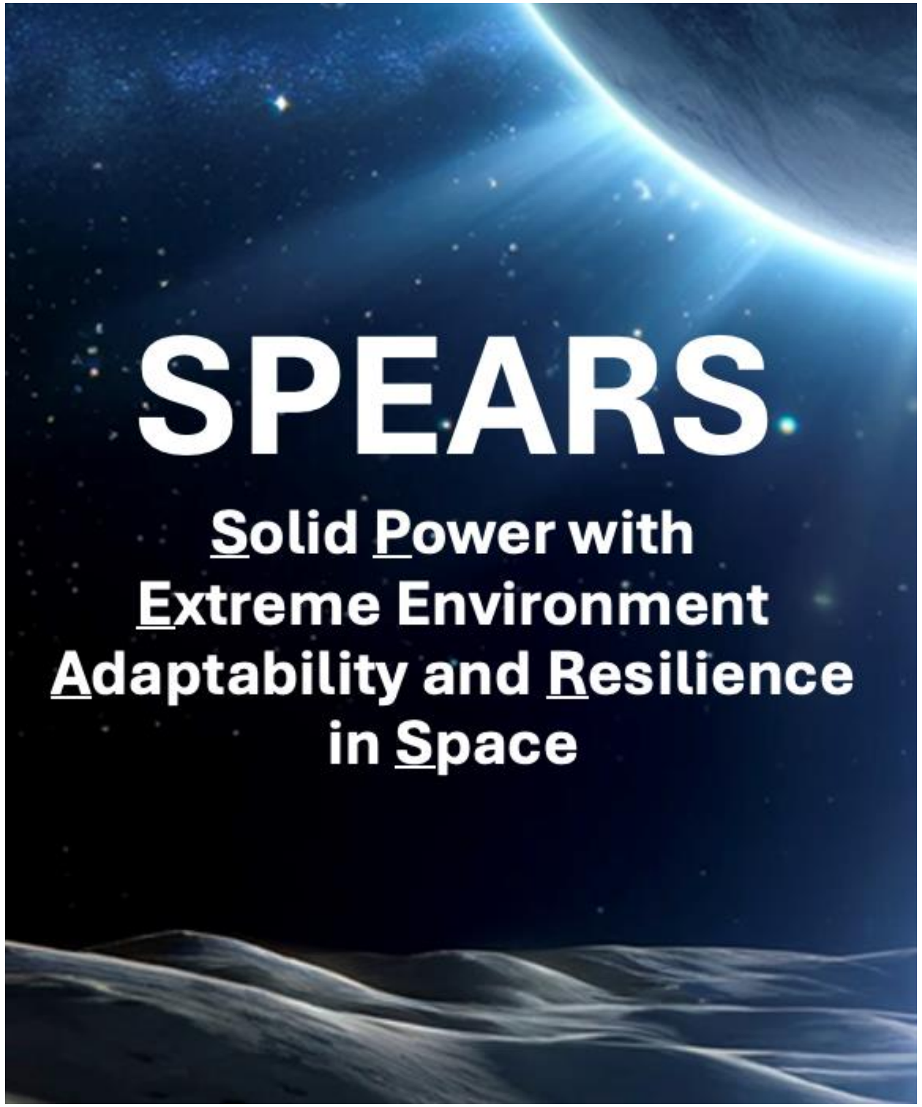
08/25/2026

SABERS

(2019-2024)

Solid-state Architecture Batteries for Enhanced Rechargeability and Safety



From **SABERS** to **SPEARS**

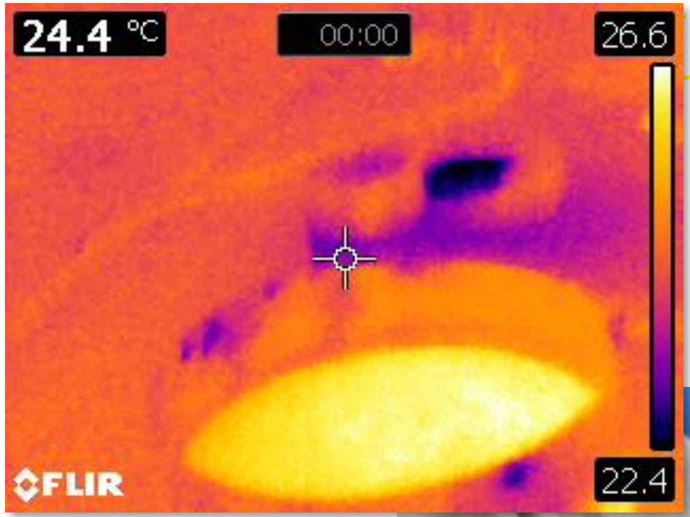
For <u>electric aviation</u>:

- **The primary barrier to electric aviation is battery performance**
  - Aerospace batteries require: **<u>safety</u>**, **<u>high energy density</u>**, high rate, long cycle life, low failure rate, lightweight packaging, and scalability
- **Conventional lithium ion batteries (LIBs) are intrinsically unsafe:**
  - With the use of organic electrolyte, conventional LIBs have narrow operational temperature range and may undergo thermal runaway when heated or overcharged

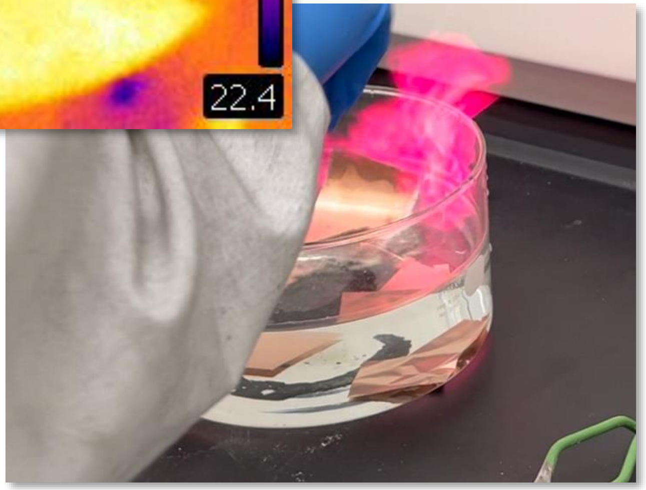
For <u>extreme space environment</u>:

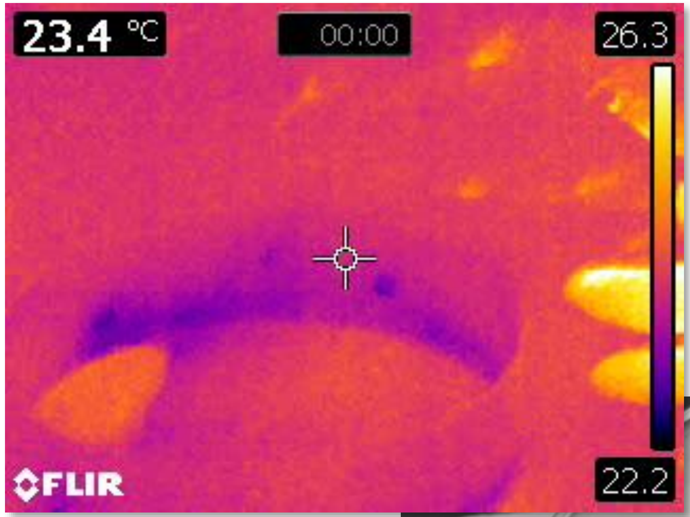
- No volatile or flammable liquids, allowing safe operation even in vacuum
- Solid-solid interfaces enable cell resiliency and longevity
- Cell performance tunable for energy, power, and durability
- Expanded temperature tolerance with extreme low temperature survivability *and* high temperature operation
- Reduced thermal management allows for lighter designs and longer missions

SSBs are Safer: Reduced Flammability

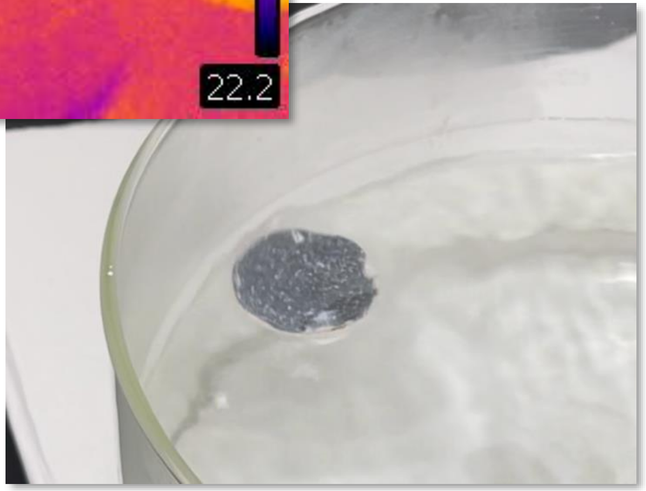


Li Metal with
Organic Liquid Electrolyte in
Conventional Pouch Cell



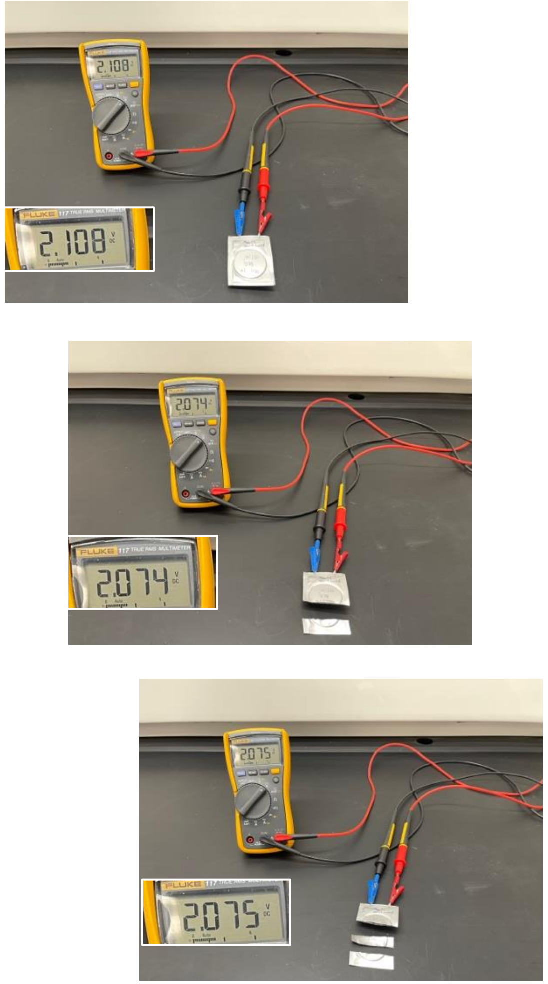


Li Metal with
Solid Electrolyte in
Solid-State Pouch Cell

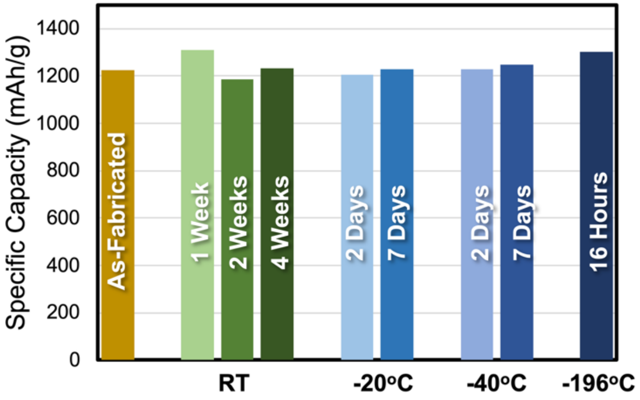


- ❑ Reaction of Li metal and water resulted in local temperature exceeding the flash point (<40^{o}C) of organic solvents that catch fire.
- ❑ Reaction of Li metal and water resulted in local temperature increase and hydrogen release, but no flammable material to catch fire.

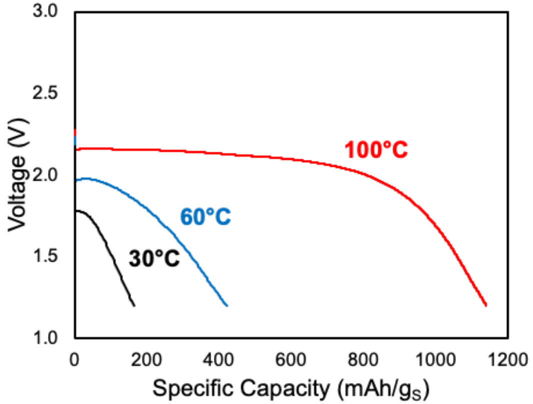
Damage Tolerance and Temperature Resilience



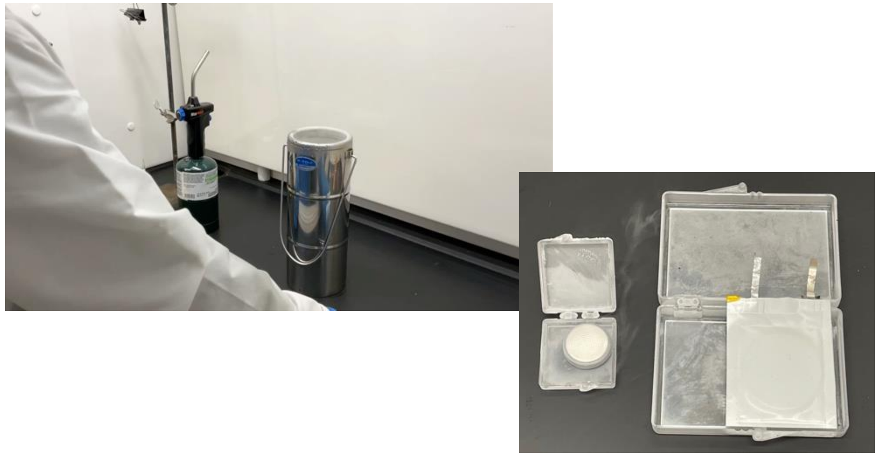
Safe Against Damage



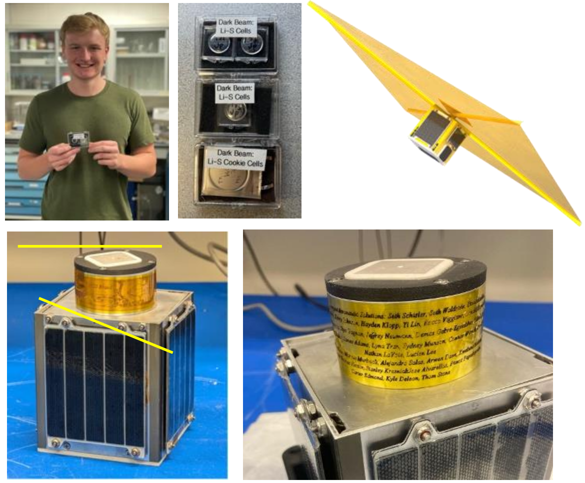
Storage in Cold and Extreme Cold



Perform in Warm and Hot



Solid-State Cells Removed from Liquid Nitrogen Reservoir

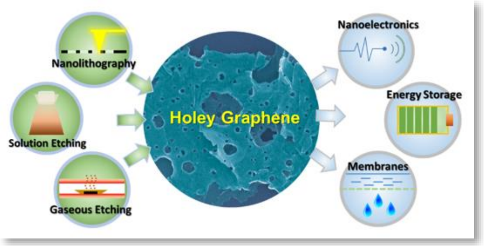


Solid-State Coin Cell in SmallSat (Launched in Jan. 2025)

The Journey with Holey Graphene

Holey Graphene Discovery

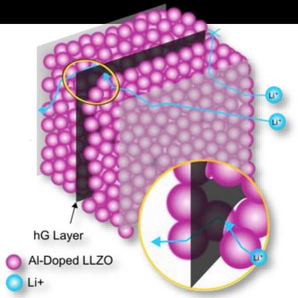
Supercapacitors



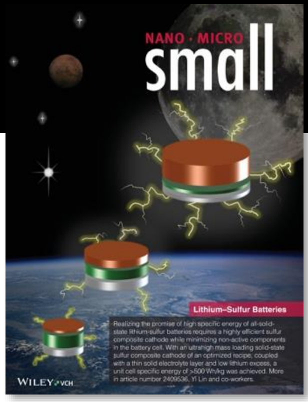
Mater. Res. Lett. **(2017)**

Li-Air Batteries

Li-S Batteries



ACS Mater. & Interfaces **(2022)**

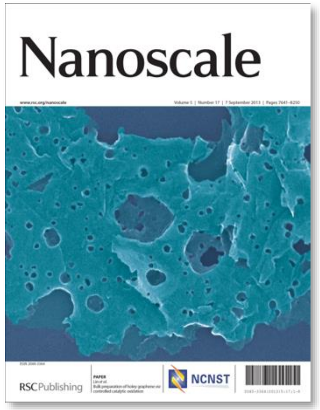


Small **(2025)**

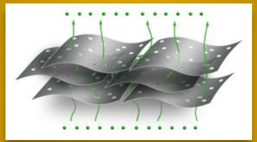
SABERS: Solid-State Li-S Batteries

SPEARS: SSBs for Space

2011 2015 2020 2025 2026



Nanoscale **(2013)**

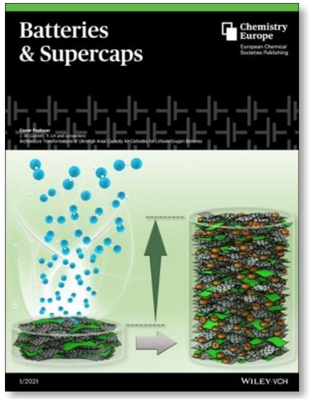


Holey Graphene Supercapacitors

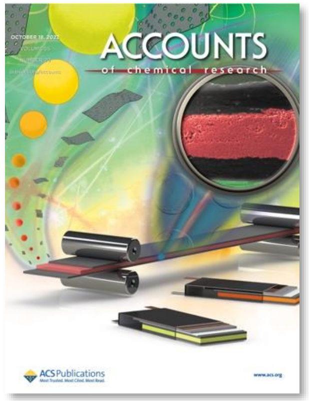
ACS Nano **(2014)**

Mars Air Batteries

CO_2-Power Conversion



Batteries & Supercaps **(2021)**



Acc. Chem. Res. **(2022)**

Battery Safety

Rechargeable Solid-State Batteries

Aviation SSBs

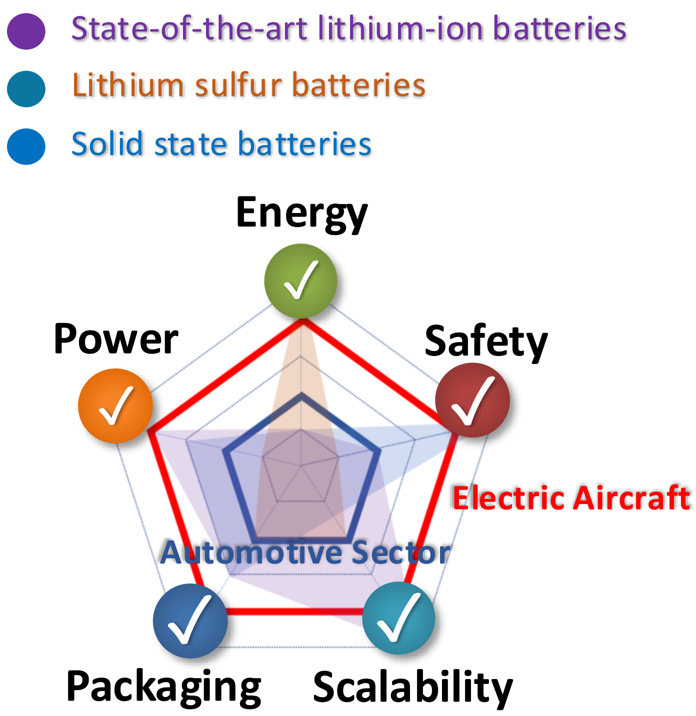
Fast-Charge

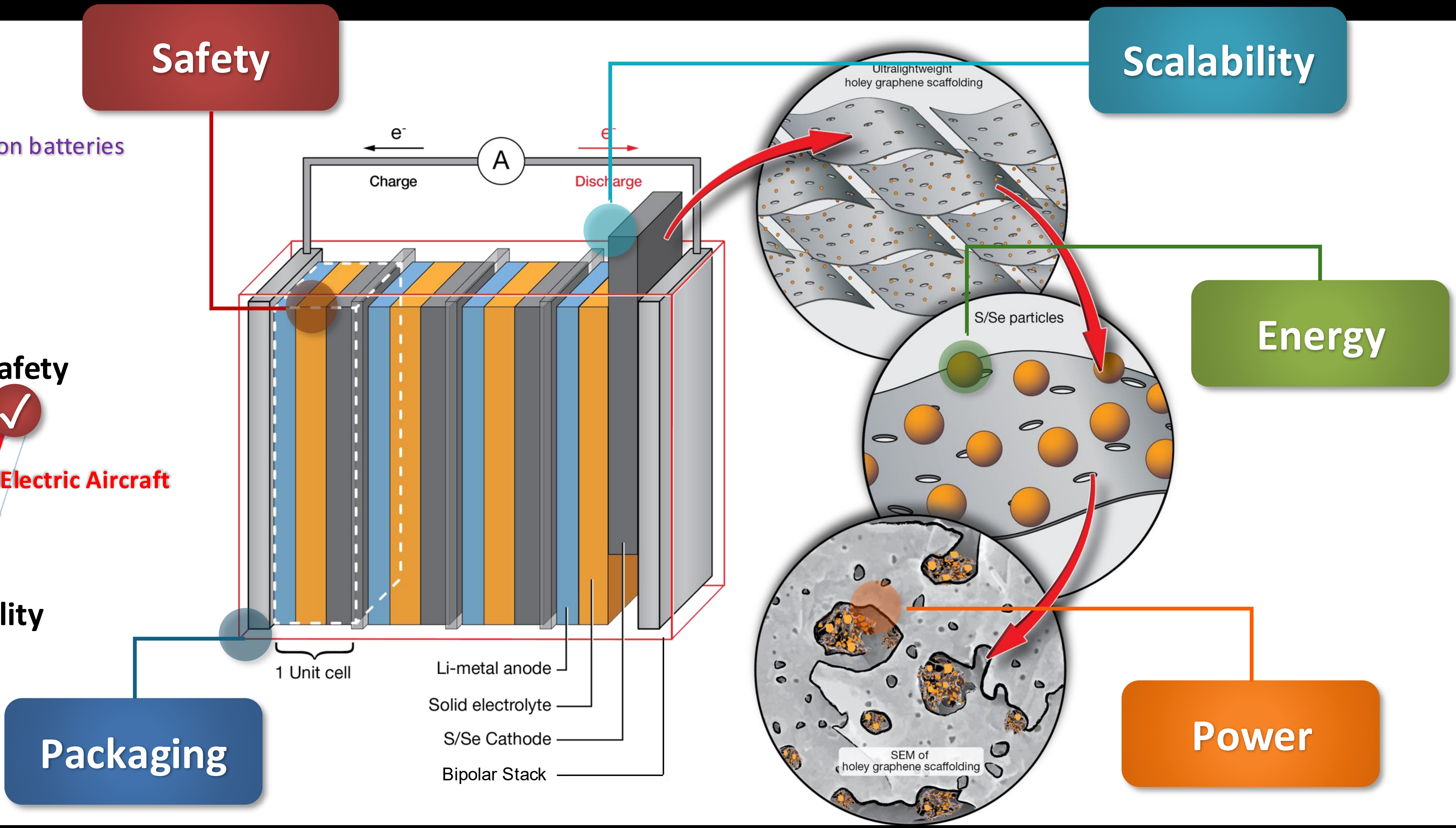
Polymer Electrolytes

Na-Based Solid-State Batteries

*Full video: https://www.youtube.com/watch?v=OGyn2PjBTN0
(or search for "holey graphene" on YouTube)

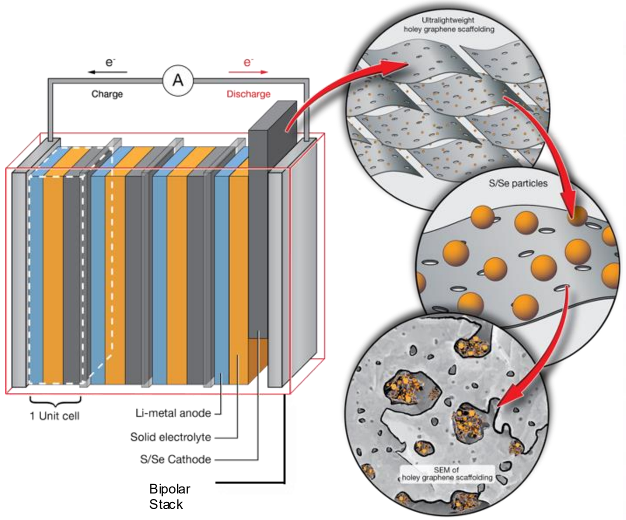
Concept of **SABERS** (2019)



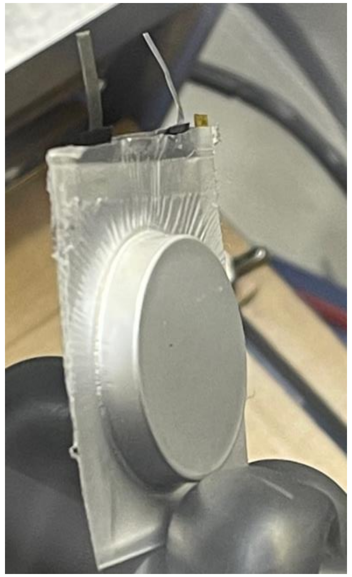


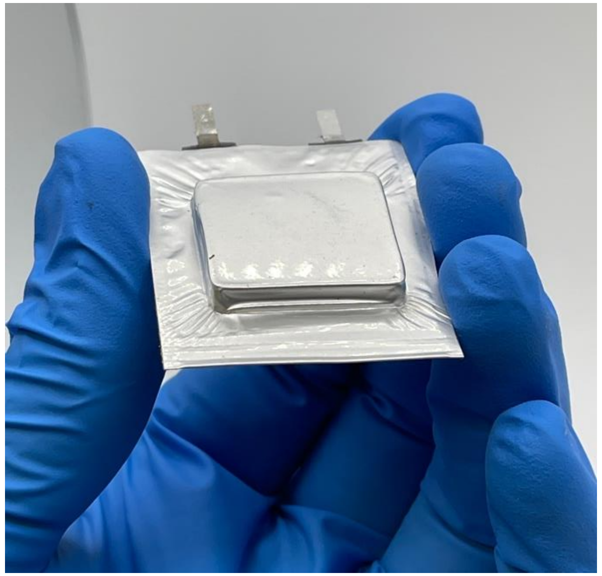
Knowledge Gained with **SABERS**

Proposed Concept (2019)



Prototype 5-Layer Li-S Bipolar Stack Pouch Cell SSBs (2024)

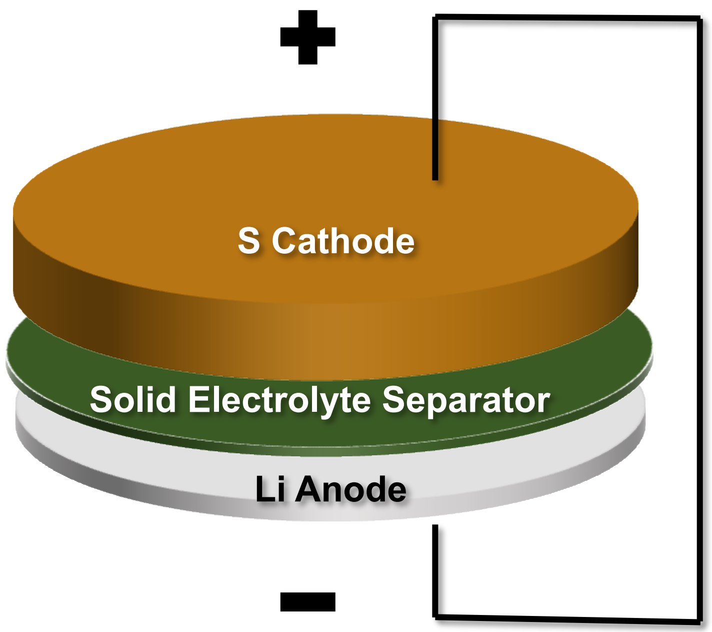




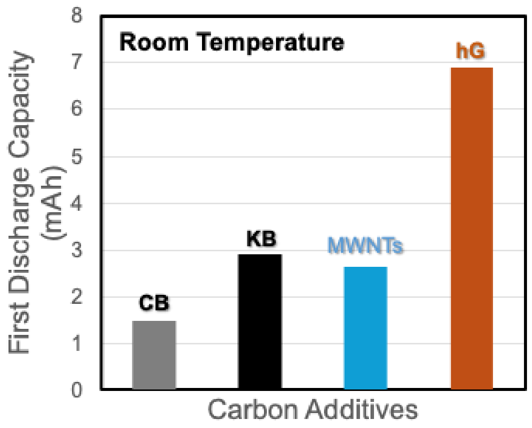
- ❑ Li-S SSBs exhibit potential to achieve >500 Wh/kg in specific energy
- ❑ Demonstration of prototype multi-layer Li-S bipolar stack pouch cell SSBs with various form factors with consistent performance
- ❑ Power and cycling performance remain challenging

Challenges in **SABERS**: Solid-State Li-S Batteries

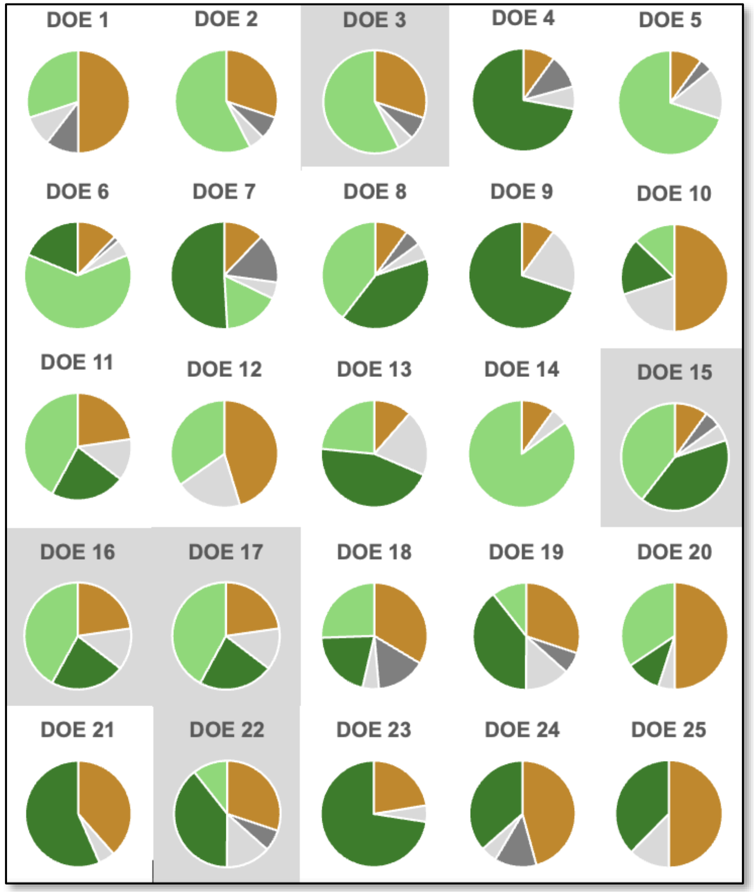
A Solid-State Li-S Cell

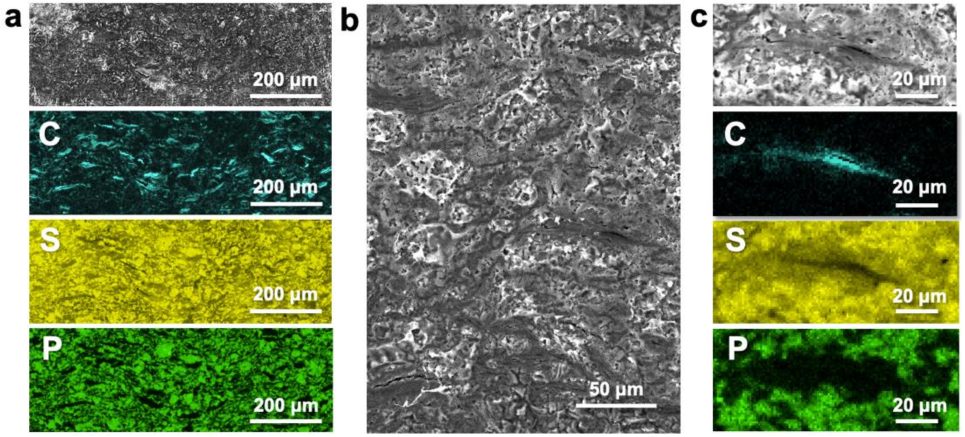


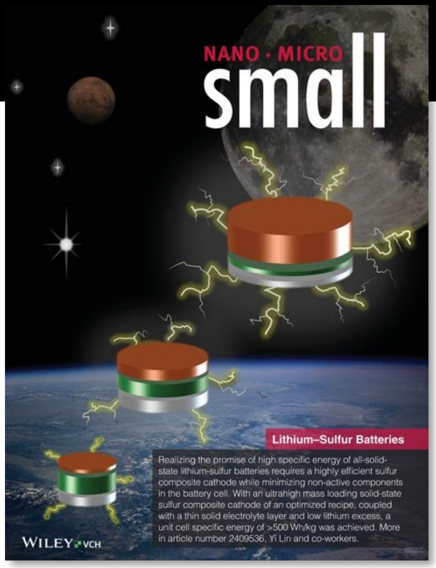
- **Cathode (Composite)**: S *and* necessary additives to make it electrically (thus **carbon**) and ionically (thus solid electrolyte) conductive
- **Solid electrolyte (SSE) separator**: A solid layer that conducts Li ion but insulates electrons
- **Anode**: Li metal

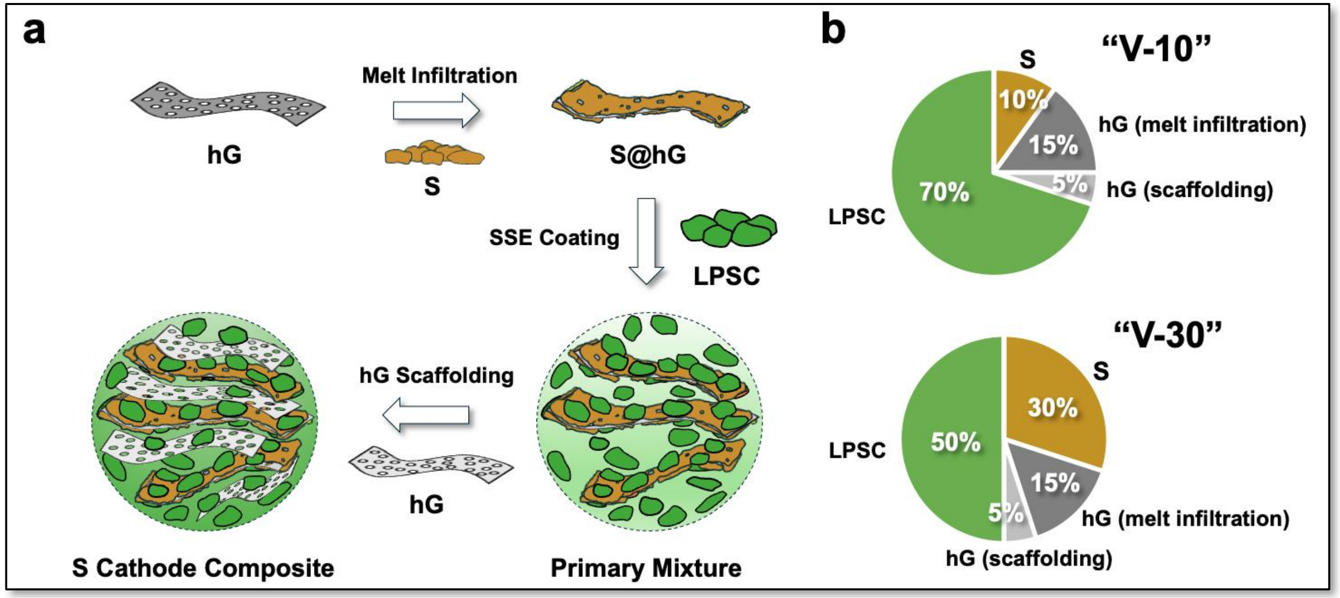


An Effective S Composite Cathode







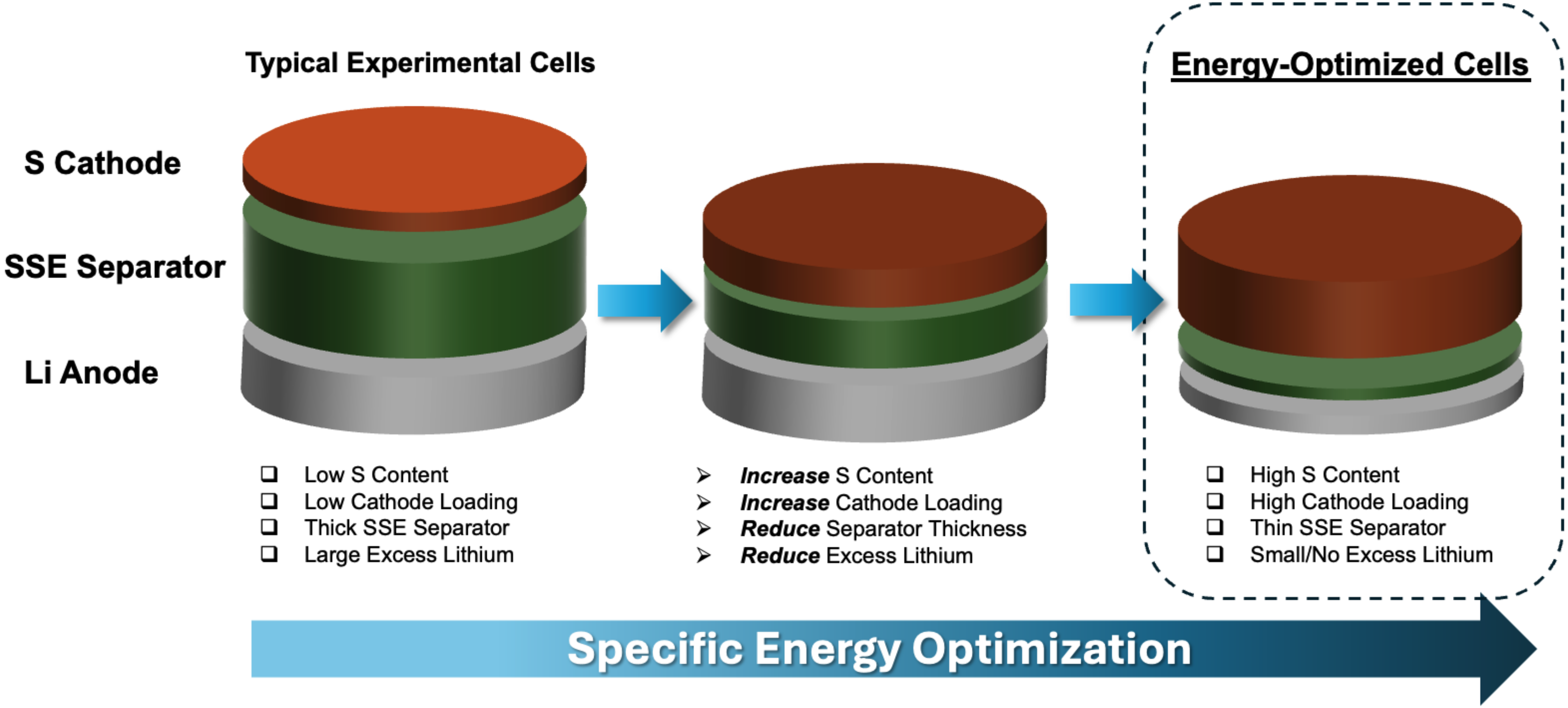


Optimized cathode microstructures enabled maximal S utilization for battery reactions.

hG: holey graphene; LPSC: Li_6PS_5Cl

Small **2025**, *21*, 202409536.

Cell Architecture with Optimized Specific Energy



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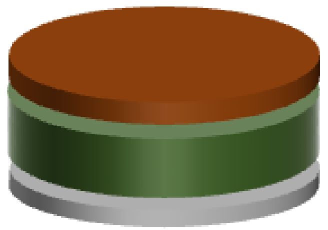
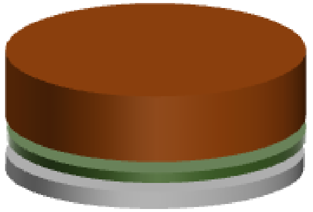
Specific Energy Premise for Li-S Chemistry

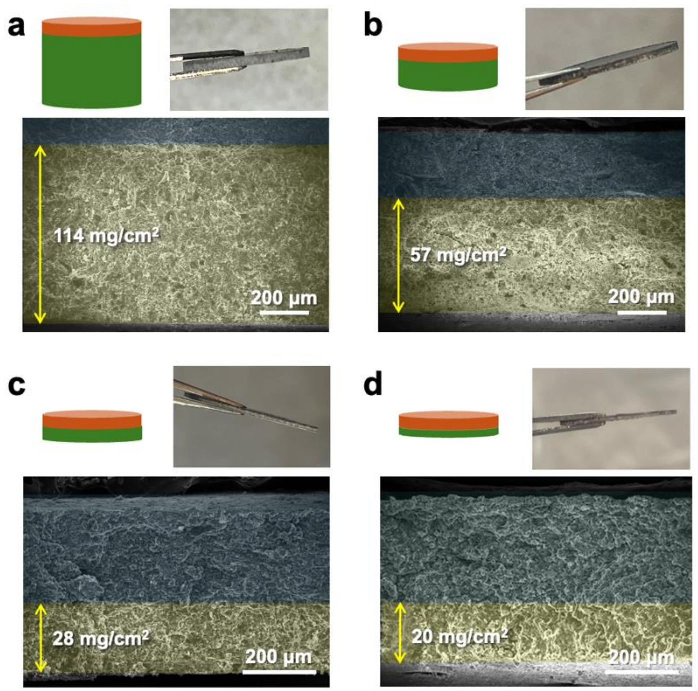


- **Thin** cathode (less S)
- **Thick** SSE
- Energy **inefficient**



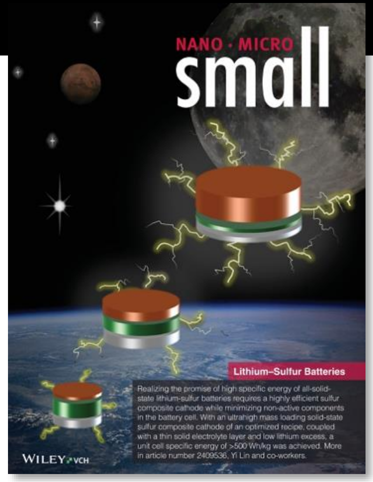
- **Thick** cathode (more S)
- **Thin** SSE
- Energy **efficient**

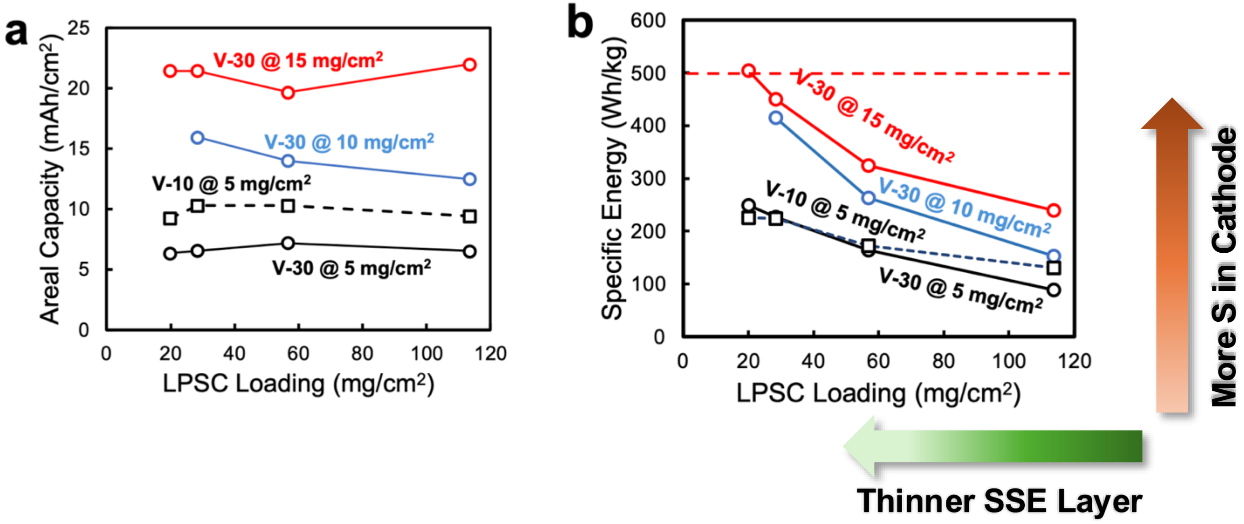
Thick S Cathode with Thin SSE Layer



Thick SABERS S Cathode + Thin SSE enabled:

- >20 mAh/cm^2 cathode areal capacity (highest reported)
- >500 Wh/kg unit cell (cathode + solid electrolyte + Li anode) specific energy (highest reported)
- All achieved with minimal stack pressure (< 2 MPa vs. 10 – 200 MPa)





Unit cell specific energy can be further improved to >600-800 Wh/kg with sufficiently thin (<100 μm) SSE layer.

Solvent-free fabrication of thick S cathode exhibits excellent performance with optimized composition and processing

- Thick cathodes are difficult to prepare using conventional solvent-based approaches.
- Nonoptimized thick cathodes typically exhibit significantly reduced performance due to poor electrical and ion transport

Small **2025**, *21*, 202409536.

Are SSBs Promising for Extreme Environments?

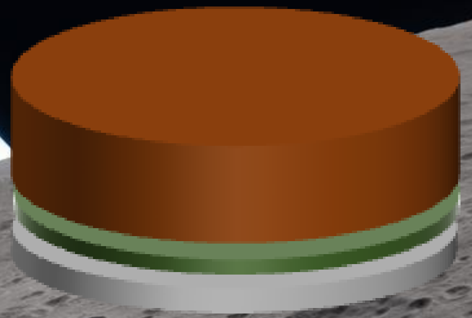
	Moderate Temperatures Normal Pressure	Low Temperatures Low Pressure	Extreme Temperatures High Vacuum
Liquid Electrolytes	✓	✗	✗
Solid Electrolytes	✓	✓	✓

Replacing liquid electrolytes with solid electrolytes expands temperature tolerance and enhances safety, making SSBs **promising for energy storage in extreme environments** **if we could resolve the critical challenges**

SPEARS: SSBs for Extreme Lunar Environment

Solid **P**ower for **E**xtreme Environment **A**daptability and **R**esilience in **S**pace

- **Wide temperature swing (lunar surface)**
- ~~High vacuum (lunar surface)~~
- Radiation (lunar surface)
- Vibration (launch)



Solid-state electrolytes for separator and cathode/anode (catholyte & anolyte)

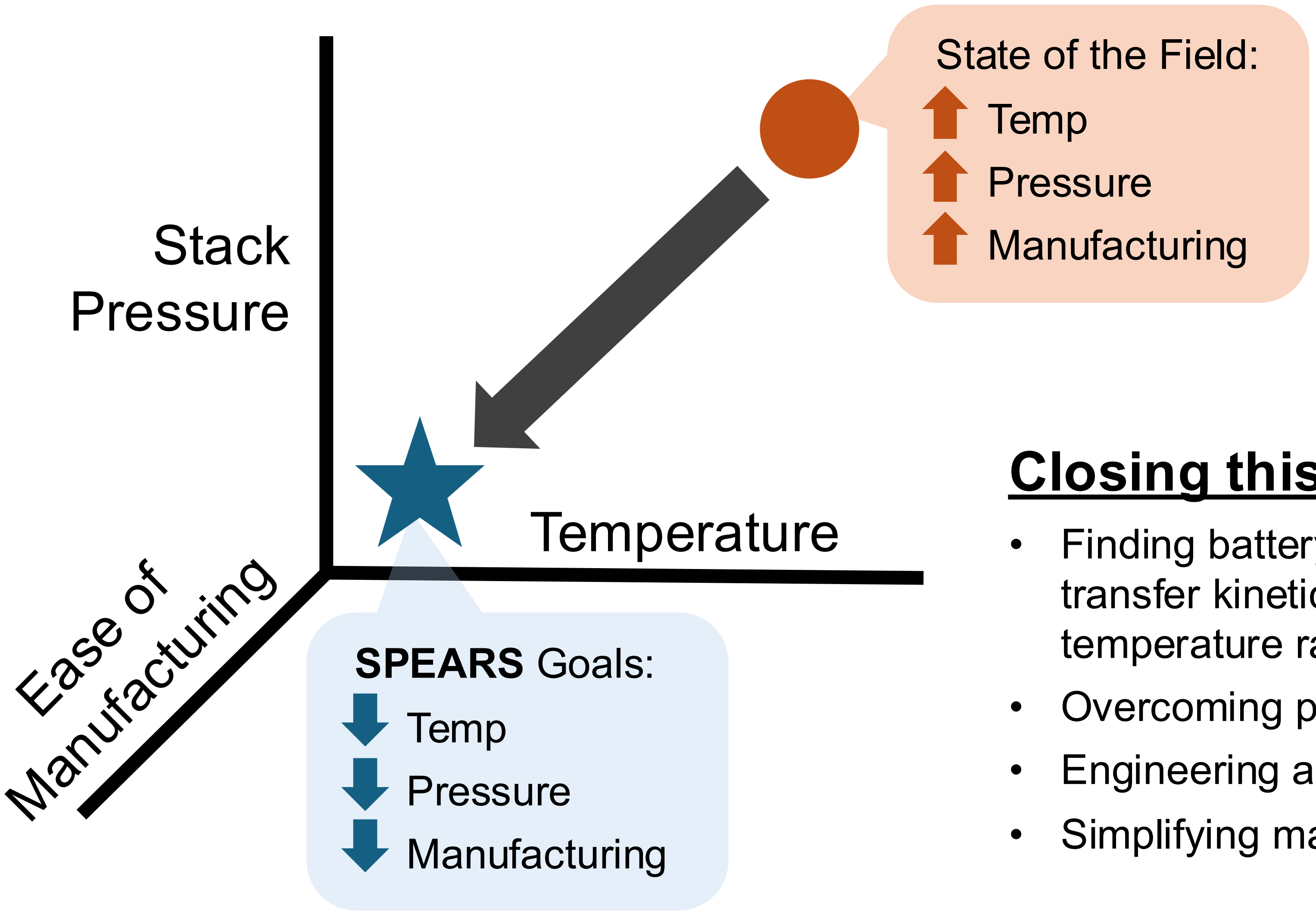
- Sufficiently high ion conductivity at low temperatures (-40°C and below)
- Stable voltage window (against cathode or anode)
- Stable against electrode active materials & carbon & binder, etc.

Cathodes and Anodes:

- Balance among energy, power, longevity
- Interface transport barriers among composite components
- Interface transport barriers with separator

Ion Transport is KEY

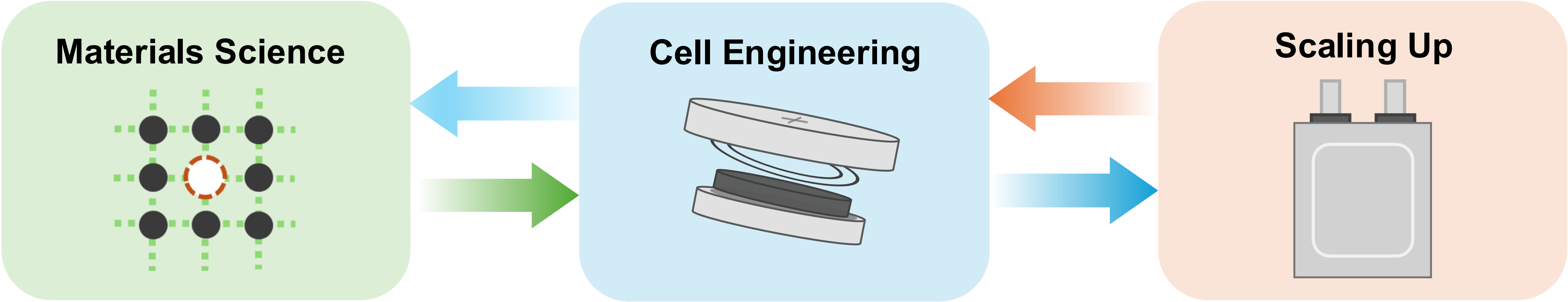
Critical Challenges for **SPEARS**



Closing this gap requires:

- Finding battery materials that support facile charge transfer kinetics and ion transport across wide temperature range with adequate stability
- Overcoming poor interfacial solid-solid contact
- Engineering and optimizing cell design
- Simplifying manufacturing processes

Scope of SPEARS



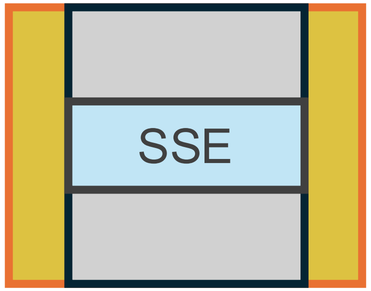
Finding battery materials with:

- Facile charge transfer kinetics
- Fast ion transport
- Adequate stability

- Overcoming poor interfacial solid-solid contact
- Engineering and optimizing cell design

- Simplifying manufacturing processes
- Engineering and designing large format cells

Quest for the Best Solid-State Electrolytes (SSEs)



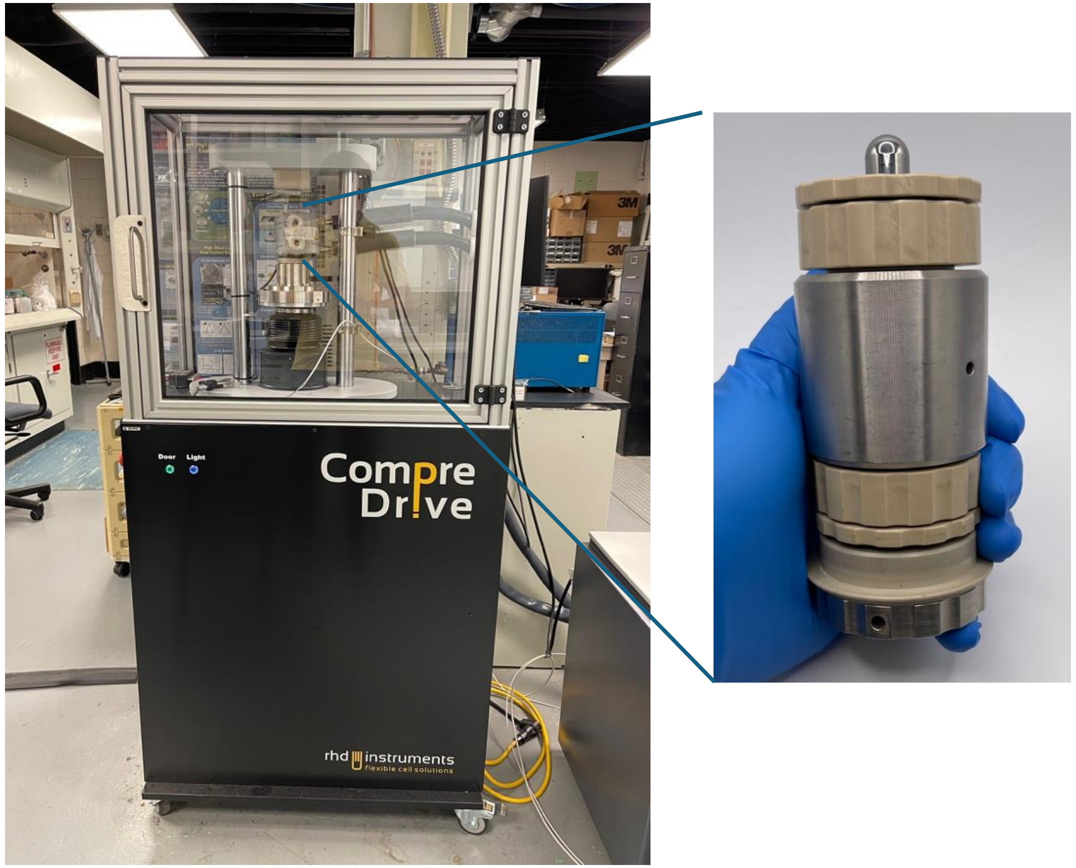
Ionic Conductivity (σ) ↑

Activation Energy (E_A) ↓

Screen and synthesize SSEs with varying chemistries and crystal structures, with a focus on low temperature performance

Additional requirements:

- Highly processible
- Stable in the required voltage window

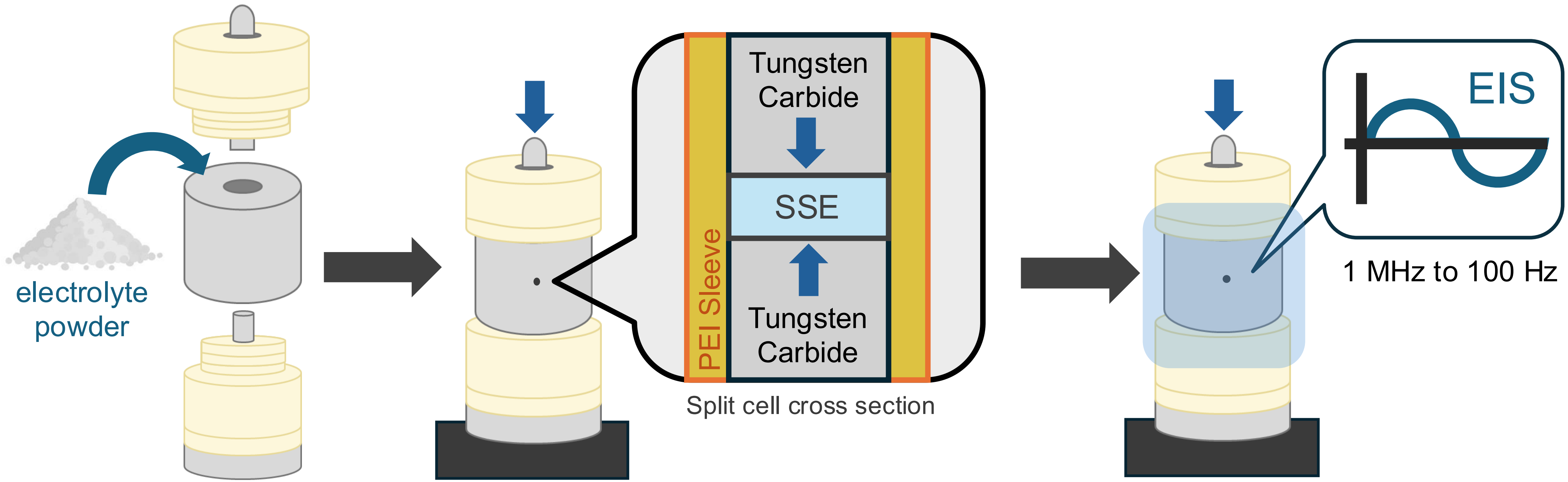


Solid-State Battery Test System with Precise Temperature and Pressure Control

Screening Protocol for SSEs

Summary of Screened SSEs (12 total):

Chemical Classification	Sulfides (8)		Halides (4)	
Crystal Structure Family	Argyrodites (6)	LISICON (2)	Amorphous (3)	Monoclinic (1)



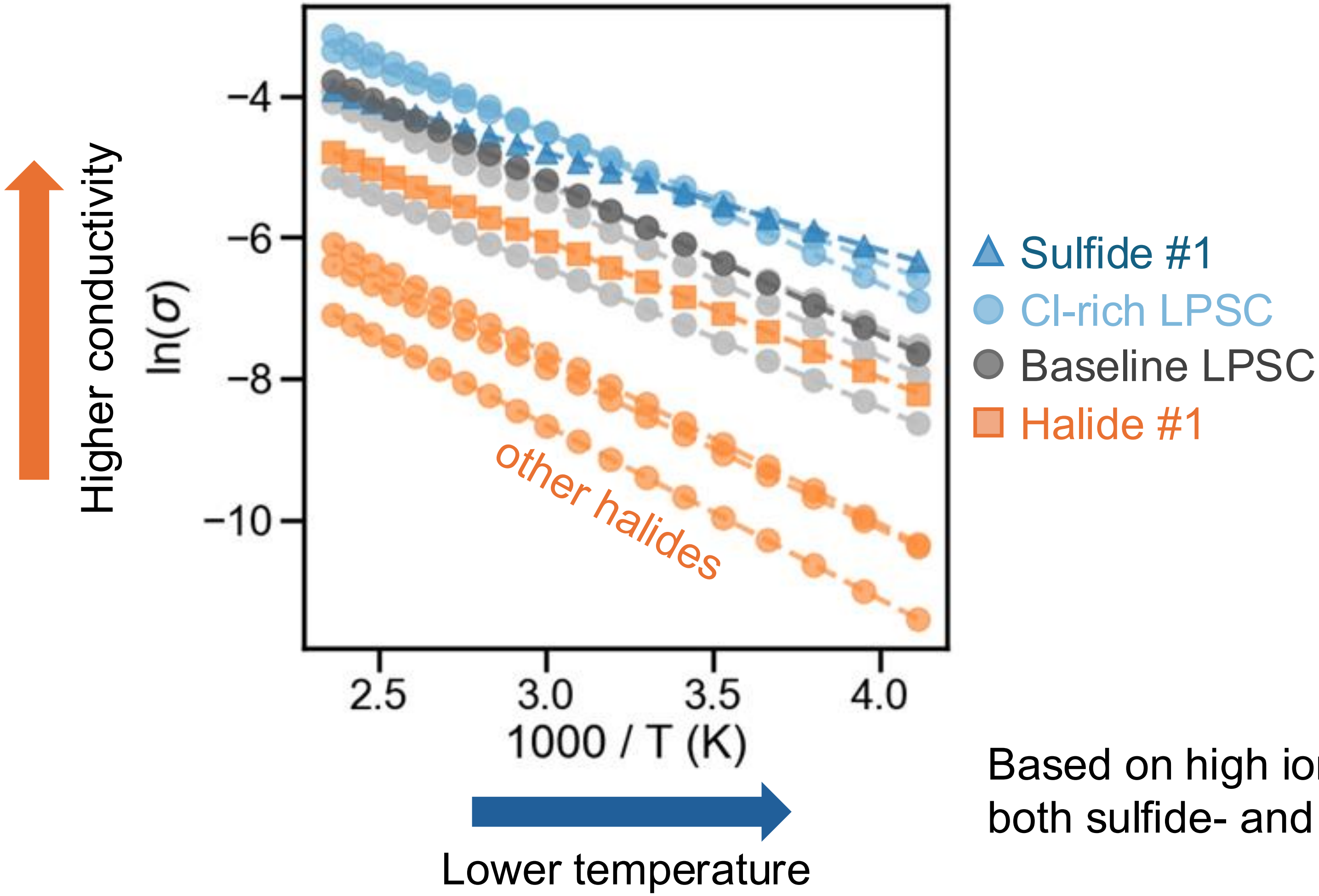
Split Cell Assembly

Densification
250 MPa, 25°C

EIS Measurements
100 MPa, -30°C to 150°C

EIS: Electrochemical Impedance Spectroscopy

Down Selecting SSEs from Arrhenius Plot

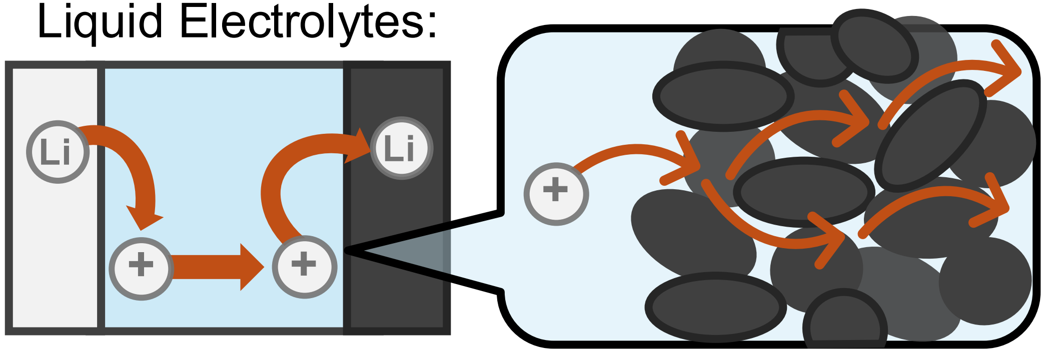


Chemical Formula	E_A (eV)	σ at -30°C (mS cm^{-1})
Sulfide #1	0.119	2.30
$Li_{4.5}PS_{5.5}Cl_{1.5}$ (Cl-rich LPSC)	0.159	1.63
Li_6PS_5Cl (LPSC)	0.189	0.68
Halide #1	0.168	0.35

Based on high ionic conductivities and low activation energies, both sulfide- and halide-based SSEs can be promising candidates.

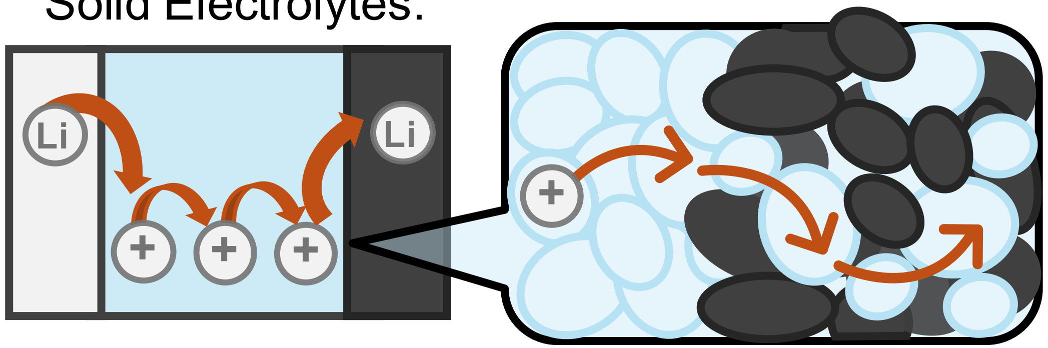
SSE as a Separator and Catholyte in Full Cells

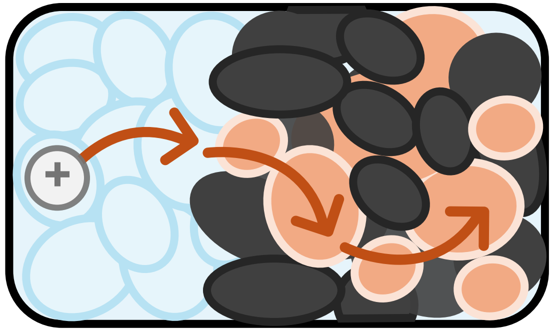
Liquid Electrolytes:



- One electrolyte that contacts the cathode and anode
- Electrolyte permeates through porous electrode structure

Solid Electrolytes:





- Can use multiple electrolytes in layers
- SSE is mixed into electrode composites

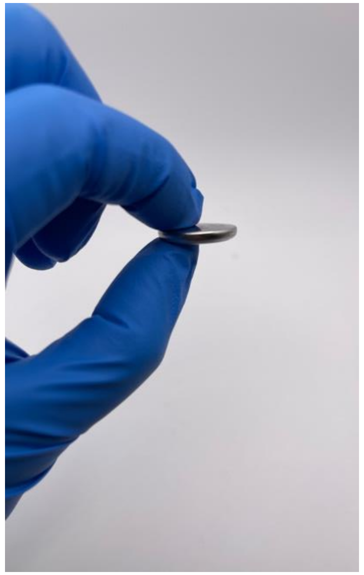
- **How does SSE choice for catholyte vs. separator affect battery performance at different temperatures?**
- **Can this information be used to guide electrode optimization?**

Experimental and Practical Cell Formats for SSBs

	Split Cells	Coin Cells	Pouch Cells
Stack Pressure Control	**Excellent**	Low	**Excellent**
Industry Standard Casing	No	**Yes**	**Customized**
Part Availability	Moderate	**Yes**	**Yes**
Cost	High	**Low**	Moderate
Field Testing Capable	No	**Yes**	**Yes**
Practical Applications	No	Moderate	**Yes**

Split Cell

Coin Cell



Pouch Cell

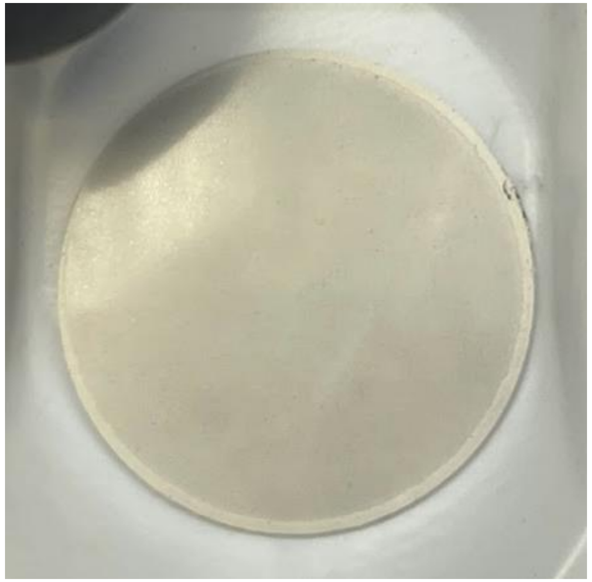
- ❑ Current academic SSB research overwhelmingly uses split/Swagelok cells with bulky casing for precise stack pressure control
- ❑ Low to no stack pressure is always preferred for most practical applications, but calls for challenges to achieve desirable energy, power, cycle life, and manufacturability.
- ❑ Our research aims to deliver cells that can be field tested in relevant environment: coin, pouch, or cylindrical

Scaling Up is Not Straightforward

Generation 1

Generation 2

Generation 3

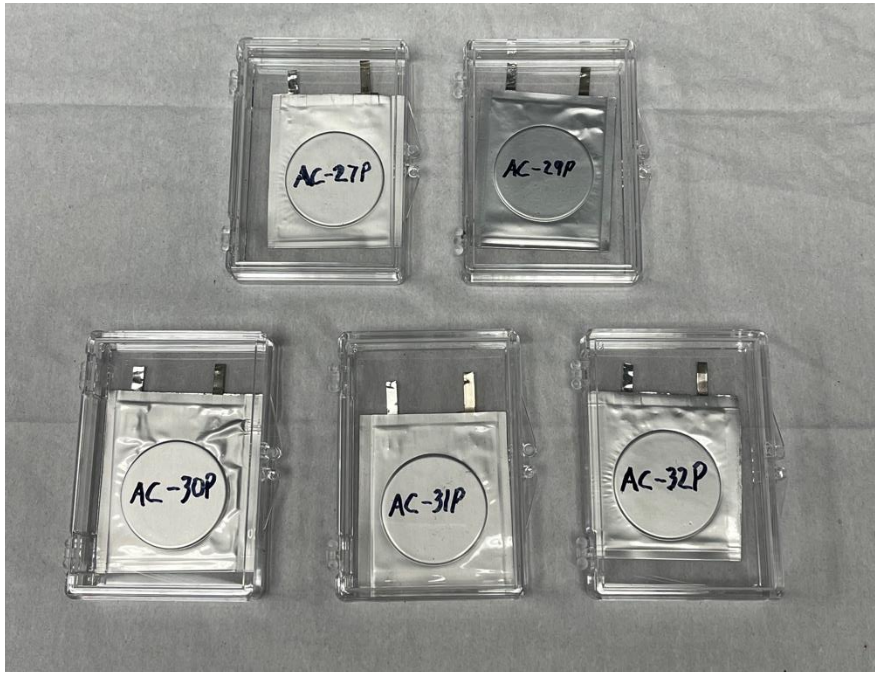


Direct scale-up from coin cell studies

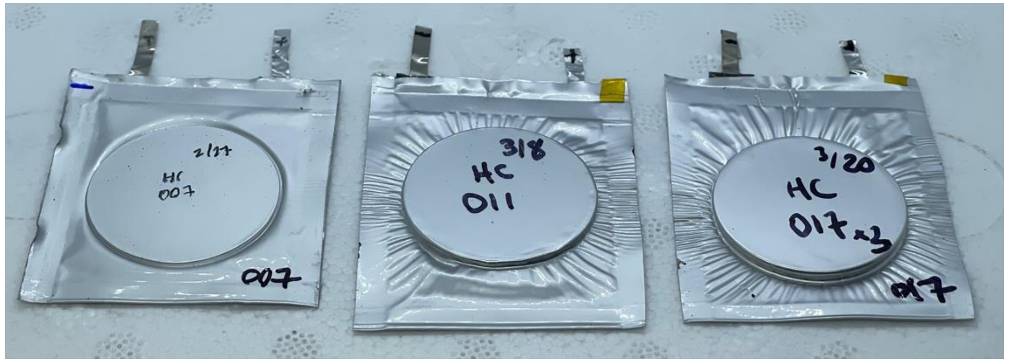
Improved dry-processing via proper use of polymer binders

Process Engineering for SSB Pouch Cells

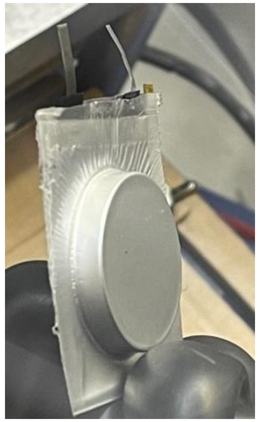
"Cookie" Cells

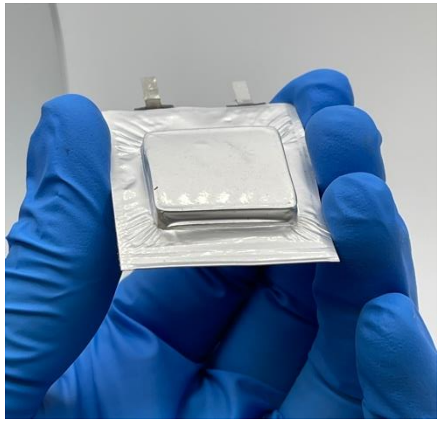


1-Layer **2-Layer** **3-Layer**



5-Layer Li-S Bipolar Stack Pouch Cells





- ❑ Establish engineering routine for high quality, small format all-solid-state pouch cells with various form factors

Summary: To the Moon and Beyond

- Solid-state batteries are the top candidate energy storage system for extreme space environment (cold & vacuum)
- Critical challenges remain to develop solid-state batteries with sufficient balance of performance
- Ion transport is KEY
- The future is bright!

Acknowledgements

- ❑**SPEARS**: NASA Game Changing Development (**GCD**) Program
- ❑**SABERS & BEAM**: NASA Convergent Aeronautics Solutions (**CAS**) Project
- ❑**Aviation SSBs**: NASA Transformational Tools and Technologies (**TTT**) Project

Current Team Members:

- ❑ Ji Su
- ❑ Sang-Hyon Chu
- ❑ Vesselin Yamakov
- ❑ Daniel Perey
- ❑ Godfrey Sauti
- ❑ Hailey Moore
- ❑ Joe Smith
- ❑ Donald Dornbusch (**GRC**)
- ❑ Rocco Viggiano (**GRC**)
- ❑ Seth Schisler (**ARC**)

Past Team Members:

- ❑ John Connell (retired)
- ❑ John Hopkins (retired)
- ❑ Glen King (retired)
- ❑ Jin Ho Kang
- ❑ Lopamudra Das

❑ Student Interns and Trainees:

- ❑ **2019 – 2022**: Elizabeth Barrios, Bryson Clifford, Christian Plaza-Rivera, April Rains, Brandon Walker
- ❑ **2022**: Daniel Caicedo, Abigail Durgin, Prabhat Jandhyala, Bona Kim, Sophie Kiley, Ashley Lam, Thomas Neufus, Rehan Rashid, Lucy Somervill, Luis Valdez
- ❑ **2023**: Melissa Chang, William Dai, Sayyam Deshpande, Amol Gupta, Ethan Higginbotham, Shane Lindsey, Claudia Lopez, Alanis Matias-Perez, Abraham Nicolson, Coby Scrudder, Aoife Zuercher
- ❑ **2024**: Demetrius Burns, Autumn Avery, Alan Cancel, Hanjing Chen, Kelsey Crawford, David Forslof, Ashley Gomez, Alison Kavanagh, Kelton McGrath, Jason Packard, Vergil Schreiber, Daniel Thornton
- ❑ **2025**: Demetrius Burns, Karen Cabrera, Alan Cancel, Marion Fowler, Mason Graves, **Cameron Jensen**, Kyle Johns, Idil Kilic, **Heesoo Kim**, Josh Klatzkow, **Rose Yesl Lee**, Jason Packard, Adi Rangyyan, Eric Schwaller, Jacob Sheldon, J. Chelsea Stephens, Justin Wang, Cole Wanner, Sean Wilkerson, Jerry Zhang
- ❑ **2026**: **Chowdhury Abid**, **Paola Marcela Algeria Orellana**, **Autumn Avery**, Yolmarie Del Valle Gonzalez, Kira Hollowed, **Cameron Jensen**, **Heesoo Kim**, Idil Kilic, **Anna LaPlante**, **Rose Yesl Lee**, Sean McInnis, Ryan Reddy, **J. Chelsea Stephens**, Gonzalo Vila, Cory Zheng